

Anisotropic transport in the overdoped High-Tc superconductors within the Van Hove scenario

Belén Valenzuela¹ and María A. H. Vozmediano²

¹*Department of Physics, University of Guelph, Ontario N1G 2W1, Canada*

²*Unidad Asociada CSIC-UC3M, Departamento de Matemáticas,
Universidad Carlos III de Madrid, E-28911 Leganés, Madrid, Spain*

(Dated: February 2, 2008)

Recent Raman experiments[1] done in $Bi_2Sr_2CaCu_2O_4$ have found that antinodal quasiparticles become insulating when the doping is varied from overdoped to optimally doped while nodal quasiparticles remain metallic. We propose a simple explanation based on the incoherence of the spectral function in the antinodal direction due to the strong scattering suffered by the quasiparticles in the proximity of the Van Hove singularity.

PACS numbers: 71.10.Fd 71.30.+h

Recent Raman experiments[1] have found a strong anisotropy of the electron relaxation in $Bi_2Sr_2CaCu_2O_4$ when the doping varies from the optimal region to the overdoped region. While the nodal quasiparticles remain metallic and hardly vary with temperature and doping the antinodal quasiparticles suffer a metal-insulator transition at $p \sim 0.16$. The result is found in the overdoped region and at high temperatures, therefore it cannot be explained with the pseudogap physics.

The Raman scattering has been proposed as a complementary technique to ARPES to explore the \mathbf{k} -dependence of the quasiparticles due to its ability to select different regions of the Brillouin zone by changing the polarizations of incoming and outgoing photons. In the point group D_{4h} of the square lattice, there are three different Raman channels: B_{1g} , B_{2g} and A_{1g} . The B_{1g} channel projects out the antinodal region of the Fermi surface, the B_{2g} the nodal region, and the A_{1g} is a weighted average over the entire Brillouin zone. The mentioned experiments refer to a strong anisotropy in the Raman signal found from a comparison of the doping and temperature dependence of the B_{1g} and B_{2g} signals.

The Fermi surface of most hole-doped cuprates around optimal doping is close to a saddle point of the dispersion relation[5]. The possible relevance of this fact to the superconducting transition as well as to the anomalous behavior of the normal state was put forward in the early times of the cuprates and gave rise to the so-called Van Hove scenario[6]. A renormalization group analysis at zero temperature using the two-patch model[7] around the Van Hove points showed that the electron self-energy has the form of the one assumed in the marginal Fermi liquid[8]. As a consequence the quasiparticle spectral weight Z goes to zero logarithmically at low energies. This result was reproduced using many-patch one-loop functional renormalization group technique[9] where it is also shown that the scattering rate at high temperatures is almost linear in frequency.

Renormalization group calculations also show the pinning of the Fermi level to the Van Hove singularity[10] what implies that for filling fractions close and below the

Van Hove filling, the low energy properties of the system will be dominated by it. These features and the phase diagram make of the VH model a sensible microscopic model to address the low energy physics of the cuprates.

In reference [3] Devereaux establishes a relation between the B_{2g} signal with the in-plane optical conductivity and between the B_{1g} and the out of plane optical conductivity at low frequencies. It is shown that these similarities work quite well in $Bi - 2212$ and $Y - 123$ but not in $La - 214$. This last discrepancy is attributed to charge ordering effects. However the general tendency shows that the in-plane momentum is at least partially conserved in the c-axis transport. Around optimal filling the optical conductivity has an incoherent behavior what matches with the result found in Raman for the B_{1g} signal (antinodal).

In ref. [4] a formalism was proposed to study the suppression of interlayer tunneling by inelastic processes in two dimensional systems in the clean limit. A relation was established between departure from Fermi liquid behavior driven by electron correlations inside the layers and the out of plane coherence. There it was shown that the out of plane hopping is always irrelevant if the Fermi level of the interacting electrons lies at a Van Hove singularity.

The renormalization group approach is a technique well suited for weak coupling, therefore it might be appropriate to study the optimal-overdoped region where the effective interaction is weaker. We propose as a possible explanation of the metal-insulator transition found in the B_{1g} signal (antinodal) the incoherence of the transport when the chemical potential of the planes is close to the Van Hove filling. For filling fractions close and below the singularity, the Van Hove filling is an attractive point in the renormalization group sense and the transport should be incoherent up to the Van Hove filling. Above the Van Hove filling the flow of the chemical potential drives the system away of the singularity area and the system recovers a Fermi liquid behavior. Within this scenario we can also understand the incoherent behavior of the c-axis optical conductivity in two different ways: either through

the relation between the Raman signal B_{1g} and the c-axis optical conductivity at low frequencies[3], or through the prediction of incoherent transport when the chemical potential is at or below the Van Hove filling[4].

In reference[1] a phenomenological model was proposed to explain the metal insulator transition in the antinodal region by invoking the opening of an anisotropic gap in the hot spots region (Van Hove region). This gap can be seen as the threshold energy where these effects take place. In the Van Hove scenario nodal quasiparticles are naturally different from antinodal, the former being strongly renormalized by scattering between the VH points. Our proposal then is compatible with the opening of an anisotropic gap, in fact it provides a physical origin for the gap. In addition the Van Hove quasiparticles have a lifetime compatible with the marginal Fermi liquid. It also agrees with the recent proposal put forward in[12] to explain the intraplane optical conductivity and the c-axis optical conductivity based on the difference between nodal and antinodal quasiparticles.

To illustrate these ideas we make a simple calculation. We compute the Raman response in the absence of vertex corrections[2]:

$$\chi''(\mathbf{q} = 0, \Omega) = \frac{2}{N} \sum_{\mathbf{k}} \gamma_{\nu}^2(\mathbf{k}) \int \frac{d\omega}{\pi} [f(\omega) - f(\omega + \Omega)] G''(\mathbf{k}, \omega) G''(\mathbf{k}, \omega + \Omega) \quad (1)$$

where $f(\omega)$ is the Fermi factor, $G''(\mathbf{k}, \omega)$ is the imaginary part of the Green function of the electron, $\gamma_{\nu}(\mathbf{k})$ is the Raman vertex corresponding to different channels $\nu = B_{1g}, B_{2g}$ and the sum is all over the Brillouin zone. The expressions for the unrenormalized Raman vertices are $\gamma_{B_{1g}}(\mathbf{k}) = a(\cos k_x - \cos k_y)$ and $\gamma_{B_{2g}}(\mathbf{k}) = b(\sin k_x \sin k_y)$ [2] where we have absorbed constant factors in the a and b parameters.

The electron self-energy in the Van Hove model has the form[7]:

$$\Sigma_{VH}(\omega) = 2\lambda\omega \log \frac{\omega}{\omega_c} - i\pi\lambda|\omega|, \quad (2)$$

where λ is a dimensionless coupling constant which is proportional to the onsite interaction, $\lambda \propto (U/t)^2$, and ω_c is a cutoff. We assume that this self-energy is a good approximation at high temperature based on calculations using functional renormalization group[9].

This self-energy is inserted in the spectral function $A(\mathbf{k}, \omega) = -2\text{Im}G(\mathbf{k}, \omega + i\delta)$ where:

$$A(\mathbf{k}, \omega) = \frac{-\text{Im}\Sigma(\mathbf{k}, \omega)}{(\omega + \mu - \epsilon_{\mathbf{k}} - \text{Re}\Sigma(\mathbf{k}, \omega))^2 + \text{Im}\Sigma(\mathbf{k}, \omega)^2}, \quad (3)$$

where $\Sigma(\mathbf{k}, \omega)$ is the self-energy due to either impurities or coupling to inelastic scattering coming from Van Hove physics and $\epsilon_{\mathbf{k}} = -2t(\cos k_x + \cos k_y) - 4t' \cos k_x \cos k_y$. The $A(\mathbf{k}, \omega)$ is inserted in the Raman scattering given by Eq. (1). The results for the B_{1g} signal in units of t are shown in Fig.1 where the standard Drude case (dashed

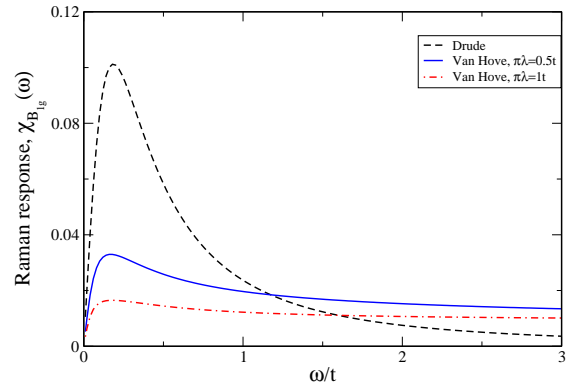


FIG. 1: Raman signal for B_{1g} channels for the conventional Drude behavior and for a system close to the Van Hove filling. The calculations have been done for $t' = -0.3t$ and $T = 300K$ for different coupling constants.

curve) with a constant scattering rate of $-\text{Im}\Sigma = 0.1t$ is shown for comparison. To the imaginary part of the self energy in the Van Hove model we have also added a constant scattering rate turning up to be: $-\text{Im}\Sigma = 0.1 + \pi\lambda|\omega|$. We can identify the peak at a frequency of twice the scattering rate $\omega = 0.2t$ in the Drude curve. For the Van Hove case we observe that the peak is already strongly reduced for a coupling constant of $\pi\lambda = 0.5t$, and can be completely washed out for bigger coupling constant, $\pi\lambda = 1t$, showing the incoherent behavior. In our argument the three curves in Fig.1 would correspond to fillings where the chemical potential is pinned at Van Hove filling (Van Hove curve for $\pi\lambda = 1t$), fillings closer to Van Hove filling (Van Hove curve for $\pi\lambda = 0.5t$), and fillings above the Van Hove filling (Drude curve). We think that higher values of the coupling constant correspond to decreasing dopings in cuprates being closer to the Mott insulator.

In order to describe more quantitatively the metal-insulator transition a full calculation must be performed varying the doping around the Van Hove filling[11]. We however believe that the simple argument provided in this paper may illustrate the physics of the problem.

Within our scheme we can also address the temperature dependence of the Raman signal found in [1]. The signal B_{2g} corresponding to the nodal quasiparticles is relatively doping independent and decreases with increasing temperature showing a conventional behavior. In contrast, the signal B_{1g} corresponding to antinodal quasiparticles varies strongly with doping showing different temperature dependence for different regions of dopings. In the strongly overdoped region ($p \geq 0.22$) both B_{1g} and B_{2g} Raman signals decrease with increasing temperature, a sign of metallic behavior. For dopings in the range $0.16 \leq p \leq 0.20$ the B_{1g} signal becomes essentially temperature independent, and finally, below optimal doping it increases with temperature. We can understand this behavior qualitatively as due to the proximity

of the chemical potential to the Van Hove singularity. Below and close to Van Hove filling the quasiparticles can be thermally excited, showing a semiconductor behavior. In the strongly overdoped region we are far from the influence of Van Hove and the behavior is the one expected in a conventional metal. We do not have a clear understanding of the intermediate region $0.16 \leq p \leq 0.22$. In reference [1] it is argued that $p = 0.22$ corresponds to a quantum critical point where the anisotropy between the B_{1g} and B_{2g} signals disappears. This feature goes beyond the scope of the present study.

In all these qualitative arguments one should bear in mind that the behavior seen in experiments is attached to the fully interacting system and not to the free one. Therefore we cannot determine where is the Van Hove filling of the free theory. Although in ARPES experiments[5] they can observe an extended singularity, the spectral function $A(\mathbf{k}_{fixed}, \omega)$ is extremely broad and cannot be thought of as quasiparticles. That means that any singularity in the density of states is washed out. This result is consistent with other experiments such as tunneling and optical measurements where no singularity in the density of states is observed. This does not mean that the Van Hove singularity is not relevant for the physics we are interested in, on the contrary, it is near the singularity where one can expect a rich physics driven by the interactions of the enhanced density of states which encodes competing instabilities and deformation of the

Fermi surface[6, 14]. The situation is similar to the one related with the presence of a quantum critical point that can be inferred by nearby anomalies at finite temperatures. In fact the Van Hove point is a quantum critical point as the divergence of the density of states and the various response functions at the critical doping occurs at zero temperature. We believe that the region of influence of the Van Hove singularity is somewhere between optimal and overdoped doping because this is the region where a dip in the Hall number is seen[13] and where the renormalized Fermi surface seen by ARPES shows an extended singularity[5].

In summary, we propose that the metal-insulator transition observed in Raman scattering in the antinodal region of BISCO is driven by the incoherence of the transport set by the strong scattering suffered by antinodal quasiparticles when the chemical potential is below or at the Van Hove singularity.

Acknowledgments. B.V. is supported by the - Postdoctoral program at the University of Guelph. Funding from MCyT (Spain) through grant MAT2002-0495-C02-01 is also acknowledged. One of us (B.V.) would like to thank Thomas Devereaux and Walter Metzner for valuable discussions. We are also very grateful to Paco Guinea for very useful conversations.

-
- [1] F. Venturini, M. Opel, T. P. Devereaux, J. K. Freericks, I. Tüttö, B. Revaz, E. Walker, H. Berger, L. Forr, and R. Hackl, *Phys. Rev. Lett.* **89**,107003-1,(2002).
 - [2] T. P. Devereaux, and A. P. Kampf, *Phys. Rev. B* **59**,6411 (1999).
 - [3] T. P. Devereaux, *Phys. Rev. B* **68**, 094503 (2003).
 - [4] M.A.H. Vozmediano, M. P. López-Sancho, and F. Guinea, *Phys. Rev. Lett.* **89** 166401-1 (2002); *Phys. Rev. B* **68**, 195122 (2003).
 - [5] A. Damascelli, Z. Hussain, and Z.-X. Shen, *Rev. Mod. Phys.* **75**, 473 (2003). J. C. Campuzano, M. R. Norman and M. Randeria, "Physics of Superconductors", Vol. II, ed. K. H. Bennemann and J. B. Ketterson (Springer, Berlin, 2004), p. 167-273 .
 - [6] J. Labbé and J. Bok, *Europhys. Lett.* **3** (1987) 1225. J. Friedel, *J. Phys. (Paris)* **48** (1987) 1787; **49** (1988) 1435. H. J. Schulz, *Europhys. Lett.* **4**, 609 (1987). R. S. Markiewicz and B. G. Giessen, *Physica (Amsterdam)* **160C** (1989) 497. R. S. Markiewicz, *J. Phys. Condens. Matter* **2** (1990) 665. D. M. Newns *et al.*, *Phys. Rev. Lett.* **69**, 1264 (1992).
 - [7] J. González, F. Guinea, and M. A. H. Vozmediano, *Nucl. Phys. B* **485**, 694 (1997).
 - [8] C.M. Varma, P.B. Littlewood, S.S.Rink, E. Abrahams and A.E. Ruckenstein *Phys. Rev. Lett.* **63**, 1996 (1989).
 - [9] See Fig. 1 in A.A. Katanin and A.P. Kampf, cond-mat/0310112, accepted in *Phys. Rev. Lett.*.
 - [10] J. González, F. Guinea, and M. A. H. Vozmediano, *Phys. Rev. Lett.* **84**, 4930 (2000).
 - [11] B. Valenzuela *et al*, work in progress.
 - [12] A. F. Santander-Syro, R.P.S.M. Lobo, N. Bontemps, Z. Konstantinovic, Z. Li, and H. Raffy, *Phys. Rev. Lett.* **88** 97005 (2002).
 - [13] Fedor F. Balakirev, Jonathan B. Betts, Albert Migliori, S. Ono, Yoichi Ando, Gregory S. Boebinger, *Nature* **424**, 912 (2003).
 - [14] C.J. Halboth and W. Metzner, *Phys. Rev. Lett.* **85**, 5162 (2000); B. Valenzuela and M.A.H. Vozmediano, *Phys. Rev. B* **63**, 153103 (2001); V. Hankevych, I. Grote and F. Wegner *Phys. Rev. B* **66**, 094516 (2002).
 - [15] Hae-Young Kee, Eugene H. Kim, and Chung-Hou Chung, *Phys. Rev. B* **68**, 245109 (2003).